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EFFECTS OF SOLID PARTICLES IN OIL ON THE LIFE OF BALL BEARINGS

J. Okamoto, K. Fujita and T. Yoshioka

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16. Abstract In this research the effect of solid particles in oil on fatigue life and wear of ball bearings was studied. Fatigue tests were run on #6204 ball bearings, operated under a radial load of 500 kg at a speed of 1150 rpm. Alumina powders (Al_2O_3) or No. 7 testing powder (JIS Z 8901) were suspended in the lubricating oil. Alumina powders (particle diameter 120 or 35 μm, 10 mg/hour or 10 mg every 8 hours) decreased bearing life by 1/10 or 2/10 of standard life in oil without suspended particles. Alumina powder (diameter 20 μm, 10 mg every 8 hours) and No. 7 powder (diameter 2-80 μm, 10 mg/hour) decreased life by 4/10-6/10. Radial clearance measurements showed wear of tested bearings, which was higher in the case of alumina powders than in oil; increase of radial clearance was -10 to 360 μm. It was from -10 to 12 μm in No. 7 powder. Bearing life in cases of solid particles was decreased by stress concentration due to projection of rolling bands caused by wear differences between pure rolling bands and slip bands in contact areas and increase of surface roughness of ball and race.

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EFFECTS OF SOLID PARTICLES IN OIL ON THE LIFE OF BALL BEARINGS

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1. Introduction

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The equations for calculating the life or rated load of ball bearings are based on the precondition that the bearings will be lubricated with clean lubricant. Clean lubricants are usually used in machinery in industrial plants, but in some cases solid particles such as bits of dirt and sand get inside the bearings used in agricultural machinery, civil engineering machinery, or automobiles. It is known that bearings under such conditions are exposed to intense wear. Hirano [1] studied the effects of solid particles on the lubrication performance by means of four-ball testing, and Kuroda [2] mixed foreign matter in the oil for lubricating cylindrical roller bearings and reported concerning their state of wear. However, the effects of foreign matter on the fatigue life are not yet known.

The study made by Committee No. 126 of the Japan Society for the Advancement of Science [3] involved testing of ball bearings in continuous and intermittent operation; it showed that the life /229
is shortened in intermittent operation. These experiments were carried out in this laboratory. However, in view of the environmental conditions at that time, there is a possibility that dust and sand in the air may have penetrated inside the bearings. Since there was a long operating time in intermittent operation, it is believed that there may have been large amounts of dust and sand mixed in.

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* Numbers in the margin indicate pagination in the foreign text.

Therefore, the writers conducted experiments to find out what effects are exerted on the life of ball bearings by the types and quantities of solid particles mixed in lubricating oil, and also to determine the degree of wear occurring in such a case.

2. Experiments

2.1. Bearings Tested

The bearings used in the experiments were single-row, deep-groove #6204 ball bearings of class 0. They were all from the same lot. Their chief dimensions are as shown in Table 1.

TABLE 1. DIMENSIONS OF THE BEARINGS TESTED (mm)

Inner diameter	Outer diameter	Width	Radial clearance	Number of steel balls	Diameter of steel balls
20	47	14	0.020-0.029	8	7.938

2.2. Tester

A life tester (Machinery Testing Laboratory Model SGH) designed for applying radial loads on single-row, deep-groove ball bearings in order to seek the bearing life was used in these experiments. The tester is shown in Fig. 1, and the part where the bearings are mounted is shown in Fig. 2.

In these figures, the bearing to be tested (#6204) is mounted on a shaft (1) which is supported on both sides by #6303Z bearings. The load is applied on the bearing to be tested by a combination of sash weights and levers. In this manner, it is possible to eliminate almost entirely all load fluctuations during

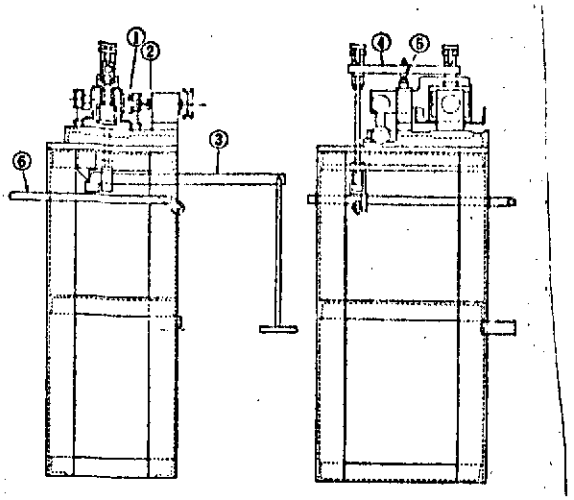

Fig. 1. Tester

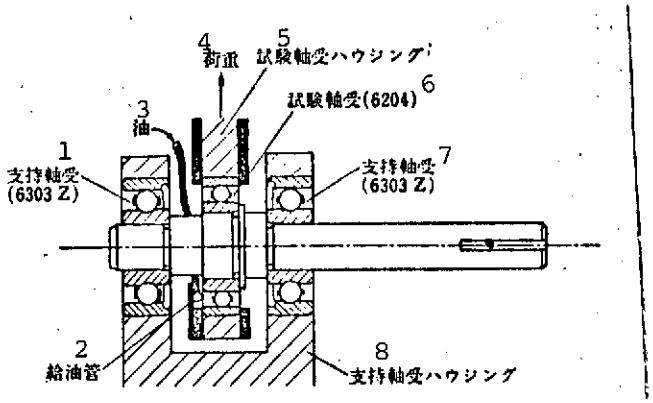

Fig. 2. Mounting of the bearing.

Key: 1. Supporting bearing (6303Z); 2. Oil supply tube; 3. Oil; 4. Load; 5. Housing for bearing being tested; 6. Bearing being tested (6204); 7. Supporting bearing (6303Z); 8. Housing for suporting bearings

long-term operations or when there are changes in the clearance. The sash weights are suspended at the tip of the arm (3). The force is expanded by a lever and is transmitted to one end of the lever (4) which is supported at the center by a knife edge (5). The other end of the lever (4) pulls the housing of the bearing being tested upwards and applies a radial load on the bearing being tested. The load can be applied or removed simply by operating the handle (6). The various supporting points of the arm and lever for loading are of a knife-edge or pivot construction. This construction is adopted in order to minimize as far as possible loading errors caused by friction.

Since the lever (4) consists of a relatively soft spring (at a load of 500 kg, the deflection at both ends of the lever is 2.8 mm), the mechanism extending from the center of this lever to the sash weights has a low natural frequency (3.3 Hz when the sash weights are 50 kg). For this reason, the oscillation frequency generated by eccentricity of the bearing being tested during operation will be far higher than this natural frequency.

Consequently, it will be absorbed as displacement between the bearing and the center of the lever (4) and will not be transmitted as far as the sash weights. As a result, it is possible to prevent fluctuating loads caused by oscillation of the sash weights.

The shaft (1) is rotated through a coupling and an intermediate shaft (2) which is connected with the motor by a V-belt.

The track wheel side of the ball bearing must be mounted exactly at right angles to the center line of the shaft. For example, when a radial load of 500 kg is applied on a #6204 ball bearing and there is a radial clearance of 10 μm, it has been demonstrated theoretically that the life will be curtailed rapidly if the inclination of the inner or outer race on the pitch circle exceeds 50 μm [4]. Due care has been taken of the following points in this tester in order to eliminate the influence of such mounting errors. Fig. 3 is an explanatory diagram showing adjustment of the mounting of the housing of the bearing to be tested. In (a), the XX' axis coincides with the center line of the shaft (1). The ZZ' axis is the loading direction. The housing is pulled up in the Z direction. The XX' axis and the ZZ' axis are orthogonal, and the YY' axis is orthogonal to both of these axes. First, the position of the housing in the XX' direction is determined by fastening the housing in (b)

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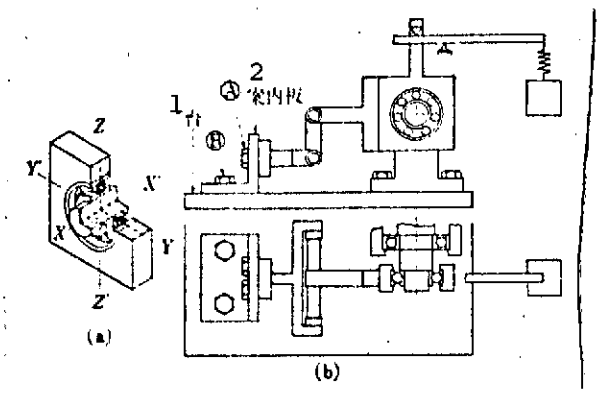

Fig. 3. Adjustment of mounting precision.

Key: 1. Platform; 2. Guide plate

on the crankshaft. Thanks to the link mechanism, the housing can move about freely inside the YZ plane, and, when the bearing to be tested is set in position, the practice followed in positioning by means of a supporting bearing is applied. Furthermore, it is necessary to adjust the inclination of the housing around the YY' axis. This is done by loosening the nut A which fastens the link on the guide plate and adjusting by turning the housing around on the YY' axis along the long hole in the arc on the guide plate. On the other hand, the inclination around the ZZ' axis is adjusted by loosening the nut B which fastens the guide plate and the platform. The housing is then adjusted by moving the guide plate along the long hole in the arc centering around the ZZ' axis in the guide plate. The adjustments around the YY' axis and the ZZ' axis were made when the bearing being tested was loaded. A dial gauge was used to measure the rectangular alignment between the housing and the shaft while making the adjustment.

2.3. Device for Mixing Foreign Matter

A belt conveyor type device for mixing foreign matter was used in cases when the foreign matter was mixed continuously in the lubricating oil. Fig. 4 shows the device mounted on the tester. The oiler is in the upper right of the figure, and the conveyor is inside the plastic cover slightly above the center. The foreign matter is lined up uniformly on this conveyor belt, and, as the belt turns, it is charged into the foreign matter charging inlet. The oil dripping down from the oiler is mixed with the foreign matter at the charging inlet and is supplied to the bearing being tested. In cases

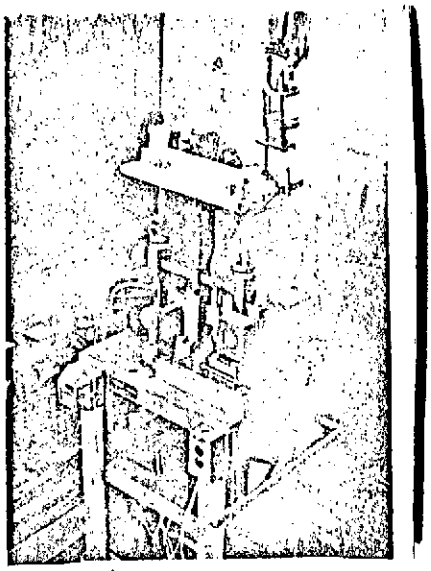

Fig. 4. Experimental equipment.

when there were small amounts to be mixed, a measuring spoon shaped like an earpick (one spoonful 10 mg) was used for charging.

2.4. Testing Conditions

The loads applied to the bearings to be tested were purely radial loads of 500 kg. The revolution speed of the bearings to be tested was set at 1150 rpm, and the mounting precision was adjusted so that the inclination of the outer race would be less than 5 μm on the pitch circle.

The shaft and the bearing to be tested were shrink-fitted at 110°C or less by a stationary fit with an interference of 10 ± 2 μm.

#90 turbine oil was used to lubricate the bearings to be tested. It was allowed to drip down at a rate of 0.5 cc/min. The foreign matter was mixed with it. Two types of foreign matter were mixed in the lubricating oil: white alundum and Type 7 powder for testing (JIS Z 8901). Their contents are as shown in Table 2. The mean particle diameter of the white alundum (WA) were measured in a microscope. The Type 7 powder for testing (JIS Z 8901) (hereinafter called "testing powder") was made by first baking Kanto loam and then pulverizing it.

The mixing conditions are as shown in Table 3. However, /231
Experiment 1 differed from the other experiments in that the lubricating method was an oil bath.

The tester was kept operating for about 8 hours every day. At other times, it was shut down with the load still applied.

The life of the bearings being tested was expressed in terms of the total operating time during which the track wheel continued

TABLE 2. TYPES OF FOREIGN MATTER MIXED IN

Foreign matter mixed in	white alundum (WA)			JIS Z 8901 Type 7 testing powder
Grain size	#150	#500	#1000	*
Mean particle diameter, μm	120	35	20	30
Chemical composition	Al_2O_3			SiO_2 34~40% Fe_2O_3 17~23 Al_2O_3 26~32 Others

* Note. Particle diameter distribution 2-80 μm

to rotate until spalling occurred. This system was adopted because the revolution speed was constant. The following method was adopted to determine whether spalling had occurred. When abnormal noises began to occur during operation, the bearing was removed and checked by visual inspection. The lifetime was measured by means of an integrating time meter interlinked with the motor of the tester.

3. Test Results

3.1. Bearing Life

3.1.1. Fundamental Experiments

Experiments were first performed without mixing foreign matter in the lubricating oil in order to obtain fundamental data.

When solid particles are to be mixed as the foreign matter, the lubricating oil will be made to drip down. Therefore, the lubricating method will differ from that used in Experiment 1, which used oil bath lubrication, and it is also possible that

TABLE 3. MIXING CONDITIONS OF EXPERIMENTS

Experiment No.	Lubrication method	Foreign matter mixed in	Grain size of foreign matter	Mixing conditions
1	Oil bath	None	--	--
2	Drip	None	--	--
3	"	White alundum	#150	10 mg/hour
4	"	"	"	200 mg at first, then oil only
5	"	"	#500	10 mg/hour
6	"	"	#1000	"
7	"	"	#150	10 mg every 8 hours
8	"	"	#1000	"
9	"	Type 7 testing powder		10 mg/hour

differences may occur in the bearing life. Therefore, drip experiments 2 were performed concurrently with the oil bath experiments 1. Fig. 5 shows the results plotted on Weibull paper. The bearing life is plotted on the abscissa of the Weibull paper, and the failure rate is plotted on the ordinate. Here, the height of the oil level in the oil bath system is half the ball at the maximum loading point of the bearing being tested. In the drip system, the amount of drip is 0.5 cc/min, but all the other conditions are exactly the same.

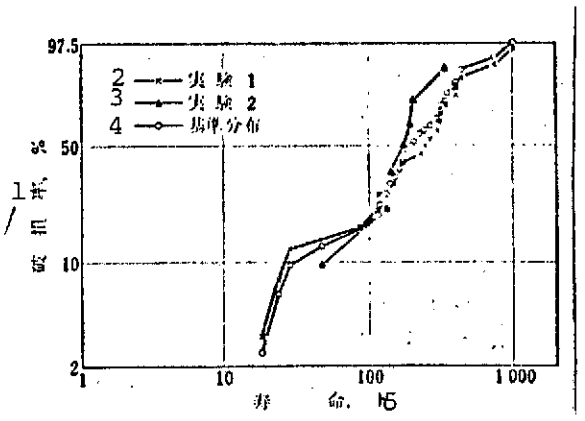

Fig. 5. Life test results (1).

Key: 1. Failure rate, %; 2. Experiment 1; 3. Experiment 2; 4. Standard distribution; 5. life, hours

As is clear in the figure, no differences occurred in the bearing life, even when there

were these differences in the experimental conditions. Therefore, both cases were regarded as belonging to the same group, and both were arranged according to the standard distribution. This is shown in the figure. In similar figures below, this standard distribution is indicated by broken lines.

3.1.2. WA Admixture Experiments

(1) Experiment 3 (WA #150, 10 mg/hour)

According to Yamashita [5], the dust blown up by the wind on a road has a chemical composition such as that shown in Table 4, and the maximum particle diameter of the dust is approximately 100 μm.

TABLE 4. CHEMICAL COMPOSITION OF DUST (YAMASHITE [5]) (UNIT: %)

Components	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	K_2O	Others
	57.79	13.56	9.19	4.73	4.10	0.76	—	3.79

Thus, first of all it was decided to use the hardest of these dust components, Al_2O_3 (WA), in order to test under the strictest conditions. WA with a #150 grain size (mean particle diameter 120 μm), slightly larger than the maximum particle diameter of the dust, was mixed in at a rate of 10 mg/hour. The results are as shown in Fig. 6. As is clear in the figure, the life was curtailed to apronounced degree, amounting to approximately 10-20% of the standard distribution. /232

(2) Experiment 4 (WA #150, 200 mg at first)

Experiment 4 was performed in order to determine whether the shortened life in Experiment 3 was caused by that fact that foreign matter was always on the contact surface during operation,

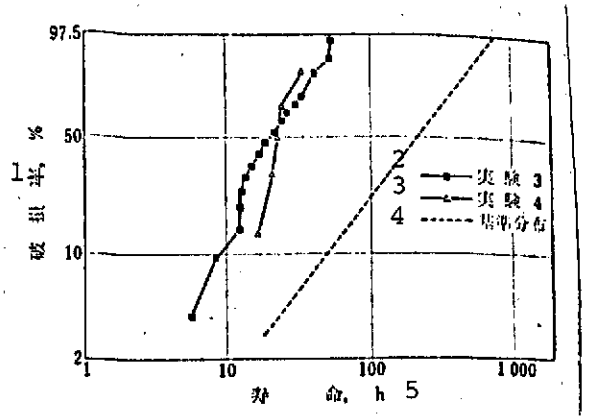

Fig. 6. Life test results (2).

Key: 1. Failure rate %; 2. Experiment 3; 3. Experiment 4; 4. Standard distribution; 5. Life, hours

thus causing stress concentration, or whether changes in the surface state of the rolling surfaces of the balls or of the track surface of the inner race caused by the foreign matter (for example, increased roughness) caused stress concentration. First, 200 mg of the foreign matter was mixed in order to change the surface state. This amount corresponded to the mean lifetime in Experiment 3 (assuming a mean lifetime of 20 hours at 10 mg/hour). After that, lubrication was continued with oil only. The results of the tests are as shown in Fig. 6. The life in Experiment 4 was approximately the same as in Experiment 3 (10-20% of the standard distribution). Consequently, one may assume that the shortened life was caused by the changes in the contact surface state rather than by the foreign matter itself.

(3) Experiment 5 (WA #500, 10 mg/h) and Experiment 6 (WA #1000, 10 mg/hour)

It was learned in the preceding experiments that WA has a pronounced influence on the life. Therefore, the experiments were then continued with smaller particle diameters of 35 μm (WA #500) and 20 μm (WA #1000). The results are shown in Fig. 7. As is clear from the figure, the lives in Experiments 5 and 6 were the same as the life in Experiment 3, in spite of the fact that the conditions were made less severe. Here again, the results corresponded to 10-20% of the standard distribution.

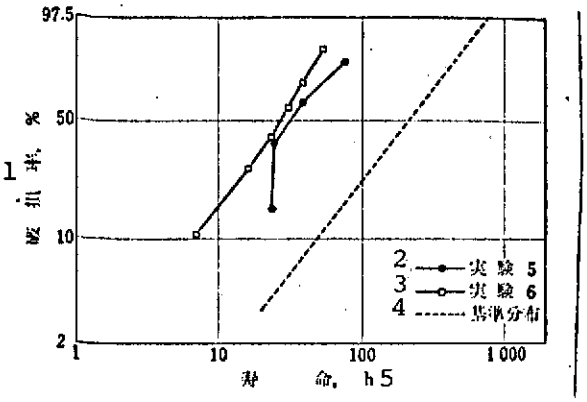

Fig. 7. Life test results (3).

Key: 1. Failure rate, %; 2. Experiment 5; 3. Experiment 6; 4. Standard distribution; 5. Life, hours

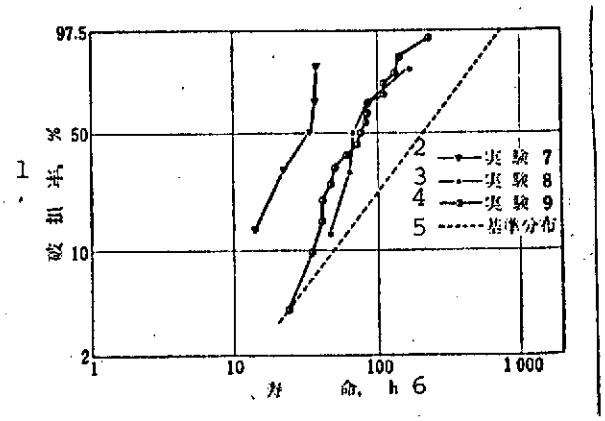

Fig. 8. Life test results (4).

Key: 1. Failure rate, %; 2. Epxeriment 7; 3. Experiment 8; 4. Experiment 9; 5. Standard distribution; 6. Life, hours

(4) Experiment 7 (WA #140, 10 mg every 8 hours) and Experiment 8 (WA #100, 10 mg every 8 hours

Experiments 7 and 8 were then performed, further reducing the amount of foreign matter mixed in and making the conditions even less severe. The results are shown in Fig. 8. As is clear in the figure, in Experiment 7, the results were still the same as those of Experiment 3-6, corresponding to 10-20% of the standard distribution. On the other hand, in Experiment 8, using a smaller particle diameter, even though the amount mixed in was the same as that in Experiment 7, the life was longer than in Experiment 3-7, amounting to 40-60% of the standard distribution.

3.1.3. Testing Powder Admixture Experiments

Thus far, the experiments had been performed using WA, which has a great hardness. Next, Experiment 9 was performed using the JIS Type 7 testing powder, which is close to natural dust. In the experiments, it was mixed in at a rate of 10 mg/hour. The results are shown in Fig. 8. The results were the same as those of Experiment 8, amounting to 40-60% of the standard distribution.

It is clear from Fig. 8 that those in experiments 8 and 9 which had a short life had the same life values as those with a short life in the standard distribution, but those with a long life had life values considerably shorter than the standard distribution. It is believed that this is attributable to the following circumstances. That is, in bearings with a short life, the regular fatigue life would be reached before the effects of /233
the foreign matter would appear, even in Experiments 8 and 9 involving solid particles, and the results would be the same as the standard distribution. However, as the life became longer, the effects of the foreign matter would appear, and differences from the standard distribution would occur.

The results of the above-mentioned experiments concerning the life are summarized in Table 5. L_{10} in the table indicates the rated life, and L_{50} indicates the median life. The value of the inclination on the Weibull paper is indicated by e, which shows the dispersion of the life distribution. Furthermore, the value of e in Experiments 4-8, in which fewer numbers were tested, was regarded as identical with that of e in Experiment 3. The values of L_{10} in Experiments 4-8 were the life values at the point where, after passing through L_{50}, the gradient line equal to e in Experiment 3 intersected with the line for a 10% failure rate on the Weibull paper.

TABLE 5. LIFE

Experiment No.	Number of experiments	L_{10} h	$\frac{L_{10}}{L_{S10}}$	L_{50} h	$\frac{L_{50}}{L_{S50}}$	e
Standard distribution	28	48	1.00	210	1.00	1.30
3	18	7.8	0.16	22	0.11	1.83
4	5	8.2	0.17	24	0.11	
5	4	13.5	0.28	38	0.18	
6	6	8.7	0.18	25	0.12	
7	5	9.9	0.21	28.5	0.14	
8	5	29.5	0.62	83	0.40	
9	17	29.5	0.62	78	0.37	1.93

The ratio between the life when foreign matter was mixed and the standard distribution was shown in the table in the L_{10}/L_{S10} column for the rated life, and in the L_{50}/L_{S50} column for the median life. The life values for Experiment 5 are somewhat larger than those in the other Experiments 3-8. It is believed that this is caused by probability phenomena because of the small number of experiments.

3.2. Examination of the Bearings After Testing

3.2.1. Wear of the Bearings

It is believed that wear occurs inside the bearings in which foreign matter was mixed. Therefore, the wear of the bearings was measured in terms of changes of the radial clearance. The results are shown in Fig. 9. On the ordinate of the figure are plotted the increases in the clearance, that is, the values of the clearance measured after the experiments from which the clearance measured before the experiments had been subtracted; and on the abscissa is plotted the bearing lifetime. The points in the figure are the values in various separate bearings. It is clear from this figure that the increase in the clearance spans a broad range of -10 to 360 μm. (The fact that the clearance assumes a negative value is believed to be because of the plastic deformation of the inner race.) The increases in the clearance caused by wear of the bearings is approximately proportional to the time, although there are certain differences

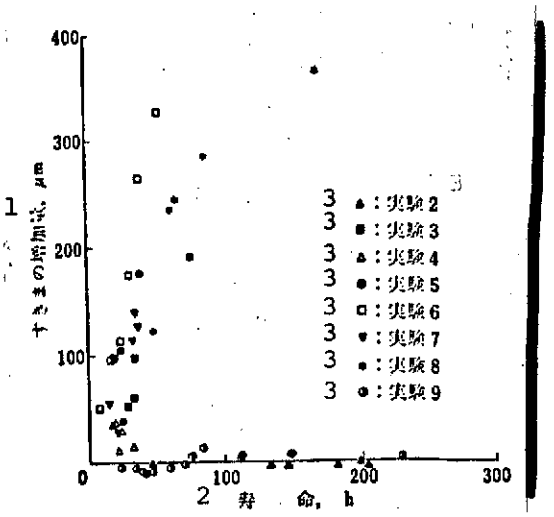

Fig. 9. Life and increases in clearance.

Key: 1. Increases in clearance, μm; 2. Life, hours; 3. Experiment ...

depending on the particle diameter of the WA in cases when the particles are mixed in continuously. On the other hand, in Experiment 4, in which the WA was put in only at the beginning, and only oil was supplied subsequently, the changes in the clearance were relatively small, amounting to only 10-30 μm.

In Experiment 9, in which the testing powder was added, and in Experiment 2, in which foreign matter was not added, there were extremely few changes in the clearance, even in those with a long life.

3.2.2. Spalling on Inner Race Track Surface

A study was made to find out whether the spalling on the inner race track surface which occurs when foreign matter has gotten inside the bearings is caused by the same fatigue as that in cases when foreign matter has not entered. Photographs of the spalling of the inner race are shown in Fig. 10; those on the right side are for Experiment 1 (oil only), and those on the left side are for Experiment 3 (WA added). As far as one could tell from observations of the spalling, there were no differences between both with respect to the shapes.

Next, a study was made of the position and state of occurrence of spalling. In cases when foreign matter was not added, spalling occurred most often in the groove bottoms, and the number was one for one inner race. The size was also not very large. On the other hand, in cases when foreign matter was added, spalling occurred more often on the pure rolling line than in the groove bottom. The number was also not limited to one in a single inner race; in some cases there were large numbers of as many as ten. The sizes were also varied, some large and some small. Fig. 11 /234 shows a typical example of spalling occurring on the pure rolling line.

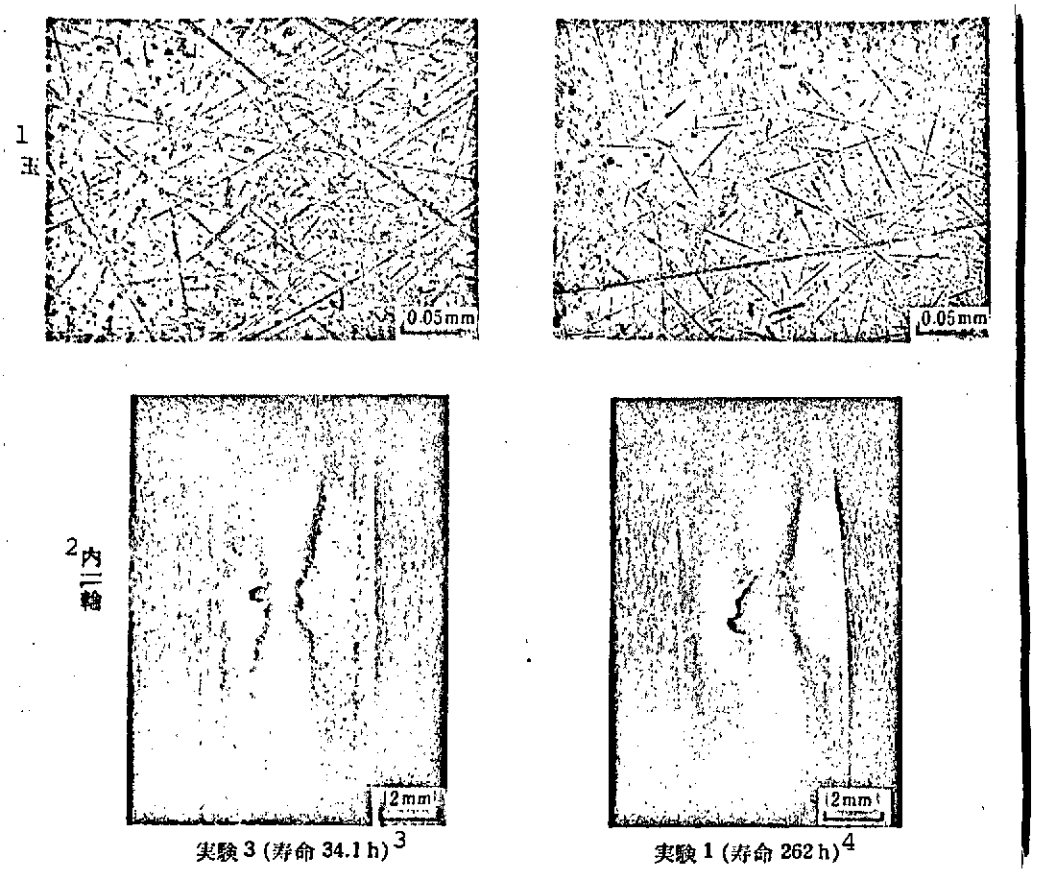

Fig. 10. Spalling of balls and surface of inner race.

Key: 1. Ball
2. Inner race
3. Experiment 3 (life 34.1 hours)
4. Experiment 4 (life 262 hours)

3.2.3. Observations of the Rolling Surface and Track Surfaces of the Bearings

(1) Observations of the Surfaces

As is clear from the examples in Fig. 10, the effects of the addition of foreign matter appear clearly in the bearings after the experiments both on the ball rolling surfaces and on the inner race track surfaces. The stripe-shaped scratches on the ball rolling surfaces increase remarkably as a result of addition of foreign matter, and they also have an increased depth. On the

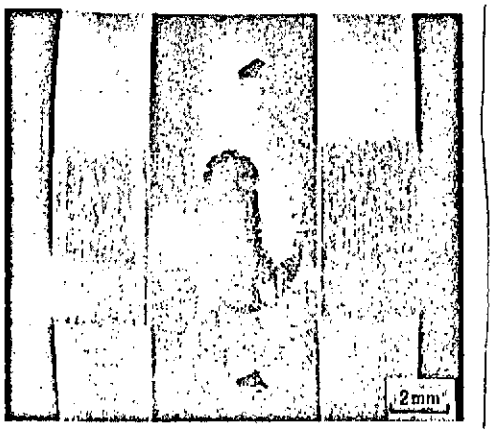

Fig. 11. Spalling on pure rolling line of track surface of inner race (Experiment 3, life 18.9 hours).

inner race, the bearings in Experiment 1 retained almost unchanged the glossy appearance of the track surface from the time of manufacture (superfinishing), and only the pure rolling lines could be seen. On the other hand, in Experiment 3, rolling marks of a pearskin-like design occurred in the inner race groove within a range corresponding approximately to the range of the contact width, and two pure rolling lines could be seen rather clearly therein.

Since there are these differences in the surface states of the contact surfaces, it was believed that there might be a connection between this and the life. For this reason, a study was made of the state of the ball rolling surfaces and the inner race track surfaces.

(2) Surface Roughness

Concerning surface roughness, the ball rolling surfaces and the track surfaces of the inner race were examined by means of a Kosaka finished surface tester. Examples are shown in Fig. 12. /235
To find the roughness on the inner race track surface, the center of the groove was measured in the circumferential direction. It is clear from these results that the surface roughness increases when foreign matter is added.

(3) Groove Shape

Concerning the inner races after the experiments, the shapes of the track grooves inside the plane parallel to the shaft were

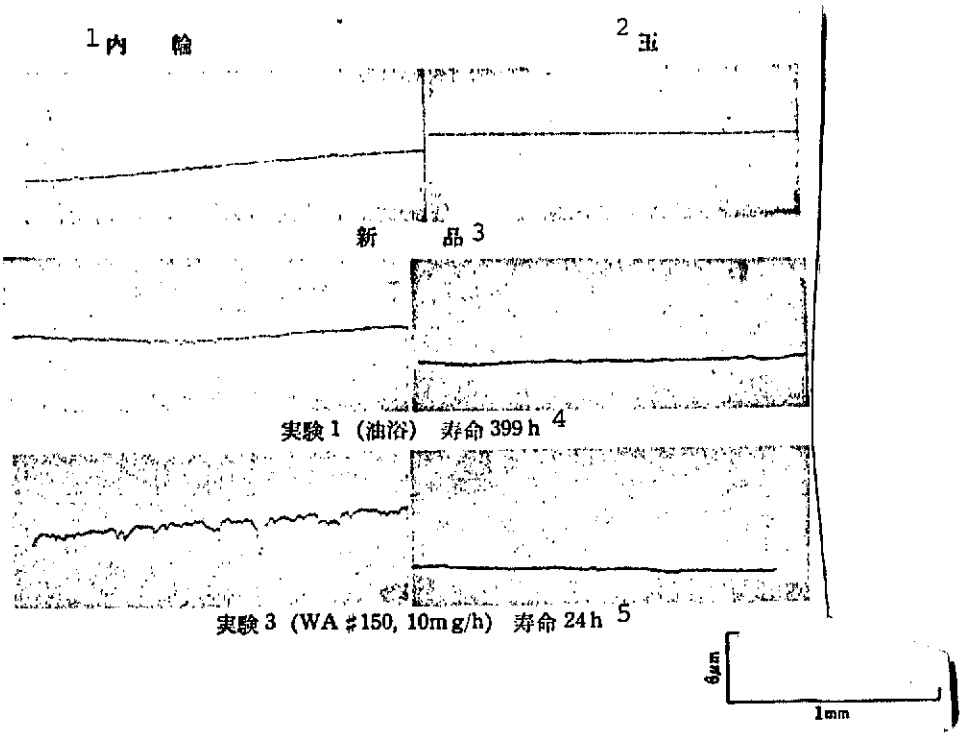

Fig. 12. Surface roughness of inner race and balls.

Key: 1. Inner race
2. Balls
3. New bearings
4. Experiment 1 (oil bath), life 399 hours
5. Experiment 3 (WA #150, 10 mg/hour), life 24 hours

measured by means of a device for measuring the out-of-roundness (Talyrond). By way of an example, the shape of the track surface of a bearing from Experiment 3 (foreign matter added) with a lifetime of 34.1 hours is shown in Fig. 13(a). (This is the same bearing as in Fig. 10.) It is clear from the figure that the track groove has two "mountains." These changes in the groove shape occur because foreign matter is caught inside the contacting surface, causing abrasive wear. The amounts of abrasion are different in the pure rolling part and in the differential sliding part, and abrasion proceeds in the manner shown by the shaded areas in Fig. 13(b). Consequently, the "mountain" parts correspond to the pure rolling region, and the "valley" parts to the differential sliding region. In the most pronounced

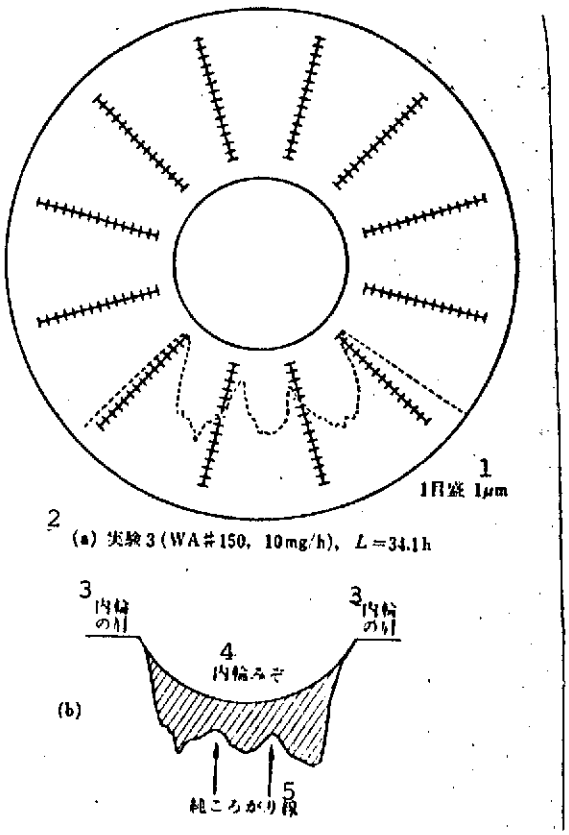

Fig. 13. Groove shapes in axial direction of inner race.

Key: 1. One calibration 1 μm; 2. (a) Experiment 3 (WA #150, 10 mg/hour), L = 34.1 hours; 3. Shoulder of inner race; 4. Groove of inner race; 5. Pure rolling lines

cases among these measurement results, there were dimensional differences of as much as about 10 μm between the abraded "valleys" and the protruding "mountains." These phenomena could not be observed in the cases when the foreign matter was not added. Furthermore, in cases when testing powder was added, these phenomena were seen only in those with a rather long life.

It was established from the above-mentioned results of observations that the changes occurring on the track surfaces /236 as a result of the addition of foreign matter include not only an increase of the roughness, but also changes in the groove shapes caused by abrasion. Furthermore, when the observations of the positions where spalling occurred and those of the groove shapes were combined, it was established that spalling tends to begin easily from the pure rolling lines which protrude within in track plane.

3.2.4. Failure Ratio of the Bearing Parts

Concerning the question whether the spalling of the bearings in experiments with foreign matter added is caused by fatigue in

the original sense or is a special phenomenon caused by the addition of foreign matter, the question was discussed in the previous section from the standpoint of the shape of the spalling. Here, let us describe the results of studies about the ratios of the various bearing parts in which spalling occurred. First of all, concerning the standard distribution, of the 27 bearings in which spalling occurred, failure occurred in the balls in only two cases. In the remaining 25 bearings, failure occurred in the inner races. Among those in which foreign matter was added, out of the 55 bearings which failed, spalling occurred in the inner races in 50 cases and in the outer races in two cases. Thus it was not possible to observe any differences between both groups in the failure ratios of the bearing parts.

4. Discussion

The following are the possible causes for the decrease in the bearing life resulting when foreign matter is mixed into the lubricating oil.

(1) Abrasive wear of the bearings causes an increase in the radial clearance, the loading zone inside the bearings becomes smaller. There are increases in the mean forces having an effect on the life of the bearings (equivalent rolling body loads), leading to a decrease of the life.

(2) Foreign matter is caught inside the contacting surfaces between the balls and the inner and outer races, the groove shapes change, and there is, at the same time, an increase in the surface roughness of the rolling surfaces. This results in pronounced microstress concentration inside the contacting surface, and the life become shorter as a result of this.

Therefore, studies were conducted of these matters. However, as was made clear in the section on the failure ratios of the bearing parts, almost all failures are in the inner races. Consequently, hereafter we shall deal only with the inner races.

4.1. Effects of the Radial Clearance

The fact that the decrease in the bearing life cannot be explained solely in terms of the effects of the radial clearance alone is obvious from a comparison of Experiments 4 and 9. That is, in Experiment 4, the life was short in spite of the fact that there were few changes in the radial clearance; while in Experiment 9, even though the changes in the radial clearance were approximately the same as those in Experiment 1, the life was 40-80% of that in Experiment 1. However, it is still possible that the radial clearance may have an effect on the life in other experiments in which there were extensive changes of the radial clearance. Therefore, let us ascertain this.

The relationship between the radial clearance c and the life ratio L/L_0 when a radial load of 500 kg is applied to #6204 deep-groove ball bearings will be as shown in Fig. 14 if Lundberg's calculations [6] are used. The ordinate in the figure plots the ratio between the life of a bearing with any clearance L and the life when the radial clearance is 0 ($L/L_0 = f(c)$). The abscissa plots the clearance c.

In cases when the bearing clearance changes together with the operating time, the life is to be found in the following manner.

When a bearing with a clearance before operation of c_1 is operated for a time t, we supposed that its clearance becomes c_t. Let us also use L_t to represent the life value corresponding to c_t. If we suppose that operation took place at this state for

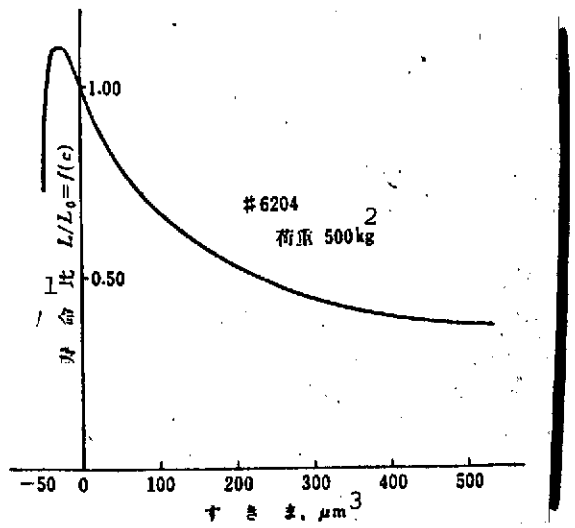

Fig. 14. Relationship between line and clearance c.

Key: 1. Life ratio; 2. Load, 500 kg; 3. Clearance, μm

time dt, the percentage of this time in operation with respect to the life of the bearing will be expressed in terms of the ratio dt/L_t. Consequently, since the sum of this ratio for the entire life L will be 1, we will obtain

$$\int_{t=0}^{L}\frac{dt}{L_t}=1 \qquad (1)$$

Here, let us assume that the ratio between L_t and L_0, the life when the clearance is 0, is $L_t/L_0 = f(c_t)$ and that the ratio between the total life L and L_0 is $L/L_0 = f(c_e)$. In this case, equation (1) will be:

$$\int_{t=0}^{L}\frac{dt}{f(c_t)L_0}=\int_{t=0}^{L}\frac{f(c_t)}{f(c_t)L}dt \qquad (2)$$ /237

Consequently, the following will be obtained:

$$f(c_e)=\frac{L}{\int_{t=0}^{L}\frac{dt}{f(c_t)}} \qquad (3)$$

Among the experiments conducted thus far, there were the greatest changes in the clearance in Experiment 6. Therefore, let us apply equation (3) to it. That is, we assumed that the clearance before operation was 20 μm and sought the relationship of f(c) from the relationship between Figs. 9 and 14. This was then integrated graphically from t = 0 to t = L (L_{10} was used as the rated life, and the clearance was 65 μm). The following is obtained from

these results and from equation (3):

$$f(c_e) = L_{10}/L_0 = 0.78.$$

On the other hand, when there are no changes in the clearance, if we use L_S for the life of a bearing with a clearance of 20 μm during operation, we obtain $L_S/L_0 = 0.89$ from Fig. 14. Consequently, the following life ratio is obtained from Experiment 6 with respect to the standard distribution:

$$L_{10}/L_S = 0.88.$$

On the other hand, in the experimental results this ratio is $L_{10}/L_s = 0.18$, much shorter than in the calculated values. It is clear from these results that, in the experimental results given here, the changes of the radial clearance do not have a very great effect and that the other factors have a greater influence.

4.2. Effects of the Groove Shape and of the Roughness

As was mentioned above, when foreign matter is added, there is less abrasion on the pure rolling line than in the other parts in the contacting surface; as a result, the pure rolling line tends to protrude, and, in many cases, the spalling begins to occur from this pure rolling line. On account of this, it is believed that there is a close connection between the changes in the groove shapes caused by abrasion and the life. Therefore, the bearings were divided up into those in which changes in the groove shape caused by abrasion were observed on the inner race track surface after the experiments and those in which such changes were not observed. Studies were made to determine whether there were any changes in the positions where spalling tends to occur easily. The results are as shown in Table 6. In counting the spallings, the following three regions were

distinguished: the two pure rolling lines on the track surface of the inner race; the part enclosed between them (the inside); and the outside part. In cases when a single spalling extended over a number of regions, they were counted in the following manner. For example, if it extended over two regions, it was counted as 1/2 of each region; and if it extended over three regions, it was counted as 1/3 of each region. However, a certain amount of error is involved because the boundaries between the different regions were not necessarily clear-cut. The numerical values in the table are the ratios to the totals of those in which the states of changes of the groove shapes are the same.

TABLE 6. CHANGES IN GROOVE SHAPES AND POSITIONS WHERE SPALLING OCCURS (UNIT: %)

Position of spalling	On the inside from the pure rolling part	Pure rolling part	On the outside from the pure rolling part
Few changes in the groove shape	60.4	29.2	10.4
Great changes in the groove shapes	13.0	81.0	6.0

It is clear from the results in the table that in cases when there are few changes in the groove shapes, when the changes in the groove shapes are observed from the groove bottom -- that is, when the pure rolling lines are protruding on account of the differences in abrasion -- spalling begins to occur from along these lines.

Next, the degree of these changes in the groove shape was measured by means of a device for measuring the out-of-roundness. The results are shown in Table 7. The mean heights of the "mountains" adjacent to the "valleys" are shown in the table.

As is clear from the table, in the experiments with addition of WA (Experiments 3-8), there were great changes in the shapes of the grooves without relation to the amounts added or to the particle diameters, and, in the experiment with testing powder (Experiment 9), these changes were observed only in those with a rather long life. /238

TABLE 7. CHANGES IN THE GROOVE SHAPES

Experiment No.	Life ratio $\frac{L_{10}}{L_{S10}}$	Changes in groove shapes caused by abrasion		Surface roughness H_{CLA} μm	Increases in radial clearance
		Lifetime h	Mean height of "mountains," μm		
Standard distribution	1.00	18.5 1000.0	0 0	0.10 0.12	5~0
Experiment 3	0.16	18.9 34.1	7 7	0.45*1 0.45	50~100
Experiment 4	0.17	17.9 33.3	4 3	0.39 0.35	10~40
Experiment 5	0.28	23.6 75.8	4 5	0.22*2 0.22	35~190
Experiment 6	0.18	7.0 52.8	5 7	0.16 0.20*3	50~325
Experiment 7	0.21	21.2 36.7	4 5	0.50 0.35	25~130
Experiment 8	0.62	47.7 168.1	5 5	0.28 0.19	120~360
Experiment 9	0.62	24.2 112.0 148.0	0 0 6	0.30 0.62*4	-10~10

*1. Life of 12.1 hours
*2. Life of 24.5 hours
*3. Life of 37.8 hours
*4. Life of 229 hours

However, since the life was the same in Experiment 8, in which there were great changes in the groove shapes on account of abrasion, and in Experiment 9, in which the changes were not very great, one cannot say that the changes in the groove shapes are the only causes of the decrease in the life in cases when foreign matter was added.

Therefore, in order to discover the relationship between the changes in the surface roughness and the life, the roughness in the circumferential direction on the track surface of the inner race of the bearings after the experiments was measured by means of a surface roughness gauge (Talysurf). The measurement results are shown in the table. Studies were also made of the roughness in the axial direction at the same time, but it was approximately the same as the roughness in the circumferential direction. It is clear from Table 7 that the roughness on the track surface is greater in Experiments 3-9, in which foreign matter was added, than in Experiment 1, in which it was not added. Among the experiments in which foreign matter was added, there was a great roughness with the WA #150 (particle diameter 120 μm) used in Experiments 3, 4, and 7, and also with the testing powder (particle diameter 2-80 μm) used in Experiment 9. In these experiments, the particle diameters were large. On the other hand, there was less roughness with the WA #500 (particle diameter 35 μm) used in Experiment 5 and with the WA #1000 (particle diameter 20 μm) used in Experiments 6 and 8. In these experiments, the particle diameters were small. It is also clear from a comparison of Tables 5 and 7 that the life decreases in cases where there is a greater roughness. This relationship between the roughness and the life displays the same tendency as the results of Uchimi et al. [7].

Since these changes in the surface roughness are the results of abrasive wear of the track surface, it is believed that they occur at the same time as the changes in the groove shapes. It is also believed that differences will occur on account of the type of the foreign matter. For example, the foreign matter may accelerate the changes in the groove shapes or may increase the roughness. Consequently, it is believed preferable to regard the decrease in the life caused by the foreign matter as being attributable to the sum of the effects of the changes in the groove shapes and the effects of the roughness.

5. Summary

The following facts were established from experiments aimed at studying the effects on the bearing life and on abrasive wear in cases when solid particles of foreign matter (white alundum and Type 7 powder for testing of JIS Z 8901) were mixed into the lubricating oil for #6204 deep-groove ball bearings.

(1) When deep-groove ball bearings are lubricated with oil containing admixtures of foreign matter, abrasion occurs, but spalling also occurs. No differences in form can be observed between this spalling and the spalling which occurs when the bearings are lubricated with oil containing no admixtures of foreign matter.

(2) When large quantities of white alundum are mixed in as foreign matter (10 mg/hour), the bearing life decreases to 1/10-2/10 of the life when foreign matter is not added to the oil. No differences in the life can be observed depending upon the particle diameters of the foreign matter (20-120 μm).

(3) When small quantities of white alundum with a particle diameter of 20 μm are added (10 mg every 8 hours), and when Type 7 testing powder is added (10 mg/hour), the life declines to 4/10-6/10 of the life when foreign matter is not added. In those bearings which have a short life in this case, the life is the fatigue life inherent in these bearings themselves, but as the life gradually becomes longer, the life is shortened on account of the influence of the foreign matter which has been added.

(4) When foreign matter penetrates inside the bearings, abrasive wear occurs, and the radial clearance becomes quite large. However, the increase in the clearance will not be the main cause leading to a shortened life.

(5) It is believed that the bearing life is shortened by foreign matter for the following reasons. That is, the foreign matter is caught up in the rolling surface, causing abrasive wear on the inner race track surface and resulting in changes in the shape so that the pure rolling part, where there is less abrasive wear than in the differential sliding parts, will protrude. At the same time, the roughness will increase on the rolling surface, thus causing local stress concentration inside the contact surface.

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